The Meteorological Magazine

April 1992

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HMSO

Met.O.1004 Vol. 121 No. 1437

The

Meteorological Magazine

April 1992
Vol. 121 No. 1437

551.508.822:551.5(09)

Some notes on radio sounding in the United Kingdom

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The earliest upper-air soundings were made by use of 'meteorographs' which were lifted by balloon or kite. Balloon-borne ones were often never recovered or only found some days later! Kite sounding gave readings the same day but with a lightning risk!! The meteorograph was a cunning device which drew a fine stylus across a smoked glass plate or other film. Movement in one direction was controlled by an aneroid capsule and in the other, at right angles, by a temperature sensitive bimetallic strip. Heights reached by captive ballons and kites could be deduced by theodolite readings and knowledge of the length of cable payed-out (30 000 ft could be reached with a train of kites). Otherwise then, as now, height (h) has to be deduced from integration of the hydrostatic equation

$$\delta h = \delta p/(\rho g)$$

where δp is the change in pressure, g is the local acceleration due to gravity and ρ is the density of the air.

Following World War II, and until recently, we used radar to get the exact range and azimuth. Elevation and range should give height by simple trigonometry but in meteorology few things are this simple. First, and most obviously, the curvature of the Earth must be allowed for, the greater the horizontal range the bigger this correction is. The radar's beam of electromagnetic radiation is affected by changes in the refractive index of the air — though not in quite the same way as light. For moderate to large elevations there is no problem, but at low elevations there may be, especially with strong hydrolapses near the surface when the radar equivalent of a mirage can form. If a target is far away and low on the horizon then elevation errors are likely, leading to quite large errors in calculating the height.

Integration of the hydrostatic equation in small steps is capable of giving very accurate height changes provided that ρ and g are known. Now g varies with location and height, so a parcel of air moving at constant geometrical height above sea level may well gain or lose potential energy, it cannot if it moves at a constant geopotential height. The geopotential height, Z, is defined by $Z{=}gz/9.80665$ where z is the geometric height.

The density, ρ, (more accurately the mean density of the layer) depends on the pressure, temperature and absolute humidity. The last is only important with dew-points above about 0 °C. The pressure is accurately measurable if the sensor is immune to the large range of temperature the exterior of the package will experience.

Temperature might be thought easy to measure but in practice it is not. The sensor should not get wet in precipitation or cloud, lest it should become a 'wet-bulb', but should be sufficiently exposed to the air (and of low thermal inertia) to give the air temperature with no lag, or at least with a well-known lag that can be allowed for. The most serious problem though is solar heating from radiation received direct, or by reflection from the clouds below, which may heat the apparatus. (Terrestrial radiation is much less and can usually be ignored). The elevation of the sun can be deduced in advance and its effects allowed for and the distribution of clouds around the sonde taken into account.

Clearly, the sonde's designers' aim is to produce a pressure element that is very well insulated and temperature insensitive, and a temperature sensor that is

totally shielded from outside radiation and hydrometeors while freely exposed to the passing air — which is difficult.

When the international radiosonde network became fully available after World War II it was soon noticed that while the air flowed smoothly across international boundaries, the contours of the pressure surfaces often did not. The higher up one went the greater the discontinuities became. It is fundamental to upper-air chart drawing, by hand or by computer, that for a given station, the observed wind velocities (calculated from the difference between two consecutive readings) are more reliable than its calculated heights (where errors accumulate). It was quickly found that the discontinuities were not so much at frontiers as between types of radiosonde and the radiation corrections applied. In the UK Meteorological Office (UKMO) it was assumed that our soundings with the Mk. II sonde were accurate but others might need adjustment. A system of automatic adjustments at 500 mb and above (Hawson corrections) ensured a consistent set of data and smooth contours on our charts. Periodic intercomparisons organized by the WMO now determine differences in a more formal way. Occasional rogue soundings can be treated along the same lines. They are compared with surrounding observations at the highest charted level, often 100 mb, and a correction decided upon. This correction is made up of smaller errors in the layers below and it is possible to make proportional corrections to other charts. However, as Hall shows in his paper, comparison with data for other times may reveal that the errors are not wholly random. In general, where problems are due to solar radiation effects, they will not be apparent in night-time soundings. But we must remember that the Sun's elevation depends on the sonde's height as well as its latitude and longitude.

Until very recently humidity has been measured on UKMO radiosondes using 'gold-beaters skin' these units were ingenious and robust but were rather slow to respond to increases in humidity and ceased to work at temperatures below −40 °C. A truely reliable, accurate, rapid response sensor, light enough to be carried on a radiosonde is a recent development. The 'humicap' element on the RS-80 is small and has a rapid response, but this starts to decline at low air densities (less than about 300 mb).

The UK Mk. III radiosonde is a system of high precision and resolution and is capable of high accuracy. Its main feature is the temperature element. This is a very fine tungsten wire wound in a spiral (rather like a spider's web) on a former above the main casing. Its time constant is only a millisecond or so and its cross-sectional area is so small that that it intercepts hardly any radiation and consequently requires no radiation corrections — in fact WMO comparisons show that it reads a little too low. However, the very fineness of the wire makes it vulnerable to accident, and operational procedures to get the best out of the system are costly in man-hours. The system includes a dedicated computer and software for 'real time' operation. The 40 kbytes of storage on the Ferranti Argus was good by the standards of the early 1970s but was barely sufficient; it is tiny by the standards of the 1990s: winds are obtained by radar tracking. During 1990 the Mk. III was phased out of UK operational use and replaced by the Vaisala RS-80. This device is smaller, lighter, more robust and is used with a modern computer; pre-calibrated by the maker, it can be made ready to fly in less than 15 minutes by one person. It is possible to add a radio receiver to pick up LORAN navigation signals and then the entire system can be run solo.

As mentioned earlier UKMO used to measure winds by radar tracking of a target attached to the sonde train; our main RSW stations are now converting to NAVAID using the LORAN system to provide fixes. Another wind-finding system used internationally is the radio-theodolite. Unlike the active radar, this is a passive instrument which measures the azimuth and elevation of the radio transmitter to which it is tuned. It suffers the same problems with refraction as radar when elevations are low; range cannot be measured directly but the height is computed from the sonde data.

551.509.313:551.509.5:551.508.822:53.088

The use of output from a numerical model to monitor the quality of radiosonde observations

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Summary

To make optimum use of meteorological observations it is essential that regular monitoring is performed to identify those of poor quality. Output from numerical forecast models has proved to be very valuable for this purpose; short-period forecasts or background fields provide accurate global reference values against which observations may be compared. This paper presents some recent results of the monitoring of radiosonde observations, and describes a number of different methods that may be used to identify cases where errors of observation, over a period of a month or more, are significantly larger than normal.

1. Introduction

Hall *et al.* (1991) described some of the ways in which output from a numerical model, in particular the short-term forecast or background values, may be used to provide valuable information on the quality of meteorological observations. Some general principles were outlined, and examples demonstrated how observations of pressure and wind from ships and buoys could be monitored. In this paper it is shown how the quality of observations from radiosondes may be assessed using similar monitoring methods, and some revealing characteristics of the errors are identified.

Radiosondes are the cornerstone of the meteorological observing network, providing in most cases detailed vertical profiles of wind, temperature and humidity of high accuracy. The importance of monitoring radiosonde performance has long been recognized, and this has been achieved at the international level through intercomparisons, sponsored by WMO, where different sondes have been carried on a single balloon. Following the first two phases of the intercomparisons in 1984 and 1985 (Nash and Schmidlin 1987), and a later phase in 1990, systematic differences between many of the sondes in regular use have been identified. The results set a standard which is obtainable under the best operating conditions; in actual practice, performance may not be the same as in a trial, as routine monitoring of the daily observations, received in real time over the GTS, readily reveals. Such monitoring may be performed in various ways. For instance, attention is frequently focused on the reported geopotential height at 100 mb as this value usually reflects the integrated effects of errors in the measured temperature at lower levels. Differences from the observed 100 mb height at neighbouring stations, or between observations made in night-time and daylight conditions are useful indicators of quality. In the absence of nearby stations, comparison is best performed against some reference values, and numerical models, which provide global fields of high quality, have often been used for this purpose (e.g. Kitchin 1989a). Much work in this field has also been performed at ECMWF and results are given in Hollingsworth *et al.* (1986) and Radford (1987). This paper will summarize what can be achieved using output from the UK 15-level model which was operational up to June 1991. Observations of temperature, geopotential and wind will be considered, but not of humidity.

2. Monitoring methods

Central to the monitoring methods described here are differences between the observed value and the value of the model background field interpolated to the observation position (referred to throughout as O−B). The background fields, derived from cycles of data assimilation, reflect the information contained in past observations as well as information relating to the structure of the atmosphere provided by the numerical model. Great advances have been made in numerical modelling in the past two decades, and today global fields are available at high resolution. Their quality is sufficiently high for them to have an important role in observation monitoring. Where the values of O−B relate to observations from one source over a long period of time, the long-term performance of the observing system may be assessed. For instance, a time sequence of values of O−B for radiosonde observations from a given station may reveal changes during the period, of larger magnitude than known errors in the background field, which can only be attributed to changes in the characteristics of the observations. Background, rather than analysis, values are used for the monitoring of observation quality because it is assumed that, being derived prior to the observation time, they are independent of the observation itself. This is probably not always strictly true; persistent systematic observation errors are not always filtered out by the data assimilation system and may influence the background field. A second basic assumption is made, namely that both the systematic and random background errors,

averaged over periods of a month or more, vary only smoothly in space. This is probably true in the free atmosphere away from steep orography and the model's upper and lower boundaries. In contrast, errors arising from inaccurate measurements may vary greatly from station to station or between national groupings of stations. Differences from background which are larger than the local average can, in most instances, be attributed to larger-than-average errors at the observing station. Errors in the background fields, which are largest in data-sparse areas, are a limiting factor in their use for observation monitoring, and indeed it is essential that all monitoring results are set in the context of estimates of model errors.

The difference between an observed value (o) and the value of the background interpolated to the observation position (b) may be expressed as

$$o-b = (o-t_o) - (b-t_b) - (t_b-t_o)$$

where t_o is the true value of the observation. If the observation is a spot value, t_o is the true spot value, while if the observation represents some time or space average, t_o is the true value averaged over time or space. Likewise t_b is the true value on the scale that the model can resolve, which in the case of the global model results presented here is approximately a 150 km × 150 km × 80 mb grid-box average. $o-t_o$ will be referred to as the measurement error, $b-t_b$ as the background error, and t_b-t_o as the representativeness error. Squaring and taking an average over many observations the following is obtained

$$\overline{(o-b)^2} = \overline{(o-t_o)^2} + \overline{(b-t_b)^2} + \overline{(t_b-t_o)^2}$$

$$= E_m^2 + E_b^2 + E_r^2.$$

It has been assumed that the various cross-product terms are zero or can be neglected. E_m, E_b and E_r are respectively the r.m.s. measurement, background and representativeness errors.

Several factors contribute to the measurement error (E_m): there are errors due to the malfunctioning of the instrumentation; there are errors arising from the wrong estimate of the pressure level; and finally, there are errors introduced on encoding, either due to truncation (the upper-air code only allows for the direction to be reported to the nearest 5°) or inaccurate ground procedures. The background error (E_b) represents numerical forecast errors on the scale that the model can resolve. There may be additional background errors if account is not taken of the time for the balloon to make its ascent and its horizontal displacement from the release point in strong winds. The representativeness error (E_r) is a measure of the sub-grid-scale detail measured by the sonde but beyond the model resolution. There will be a contribution to E_r from fine structure in the vertical (e.g. temperature changes across an inversion or strong vertical wind shear through a jet stream) as well as from mesoscale features with horizontal scales less than 150 km.

Kitchen (1989b) has estimated values for many of the components of O−B listed above using observations from the UK operational radiosonde network. He finds that E_m is the smallest of the three components of O−B (0.6−1.5 m s^{-1} for wind and 0.06−0.16 °C for temperature) while E_r is typically 2.5−3.0 m s^{-1} and 0.6−0.8 °C for wind and temperature respectively. He shows that a failure to interpolate the background field in space and time to the actual balloon position only leads to large errors in the relatively uncommon cases where the observations are valid 3 hours from the validity time of the background field or the sonde is 100 km downwind of the point of release.

In the monitoring results presented in the next section the background values are taken from the UK operational global model valid at the main synoptic hour (00, 06, 12 or 18 UTC) nearest to the observation time. Interpolation in time has not been performed between model fields, nor has the downwind displacement of the sonde been taken into account. This will lead to errors, as discussed above, but they are not thought to be large on average; in the case of operational radiosondes where most ascents start at, or one hour prior to, one of the main synoptic hours and take perhaps 60–90 minutes before balloon burst, the difference between the actual observation time and the validity time of the model field is seldom more than 1 hour.

For most radiosonde observations the vertical profile obtained from the full TEMP report contains far more detail than is available from the 15 levels of the numerical model. To achieve the best match between observation and background, the reported profile has been averaged across each of the model layers to give a layer-mean value. By smoothing the data in this way its vertical resolution is reduced to exactly that of the model and the contribution to E_r from fine structure in the vertical is eliminated.

3. Monitoring results

Fig. 1 shows vertical profiles of the mean and r.m.s. O−B differences in the 3-month period October–December 1990 at Hemsby (53° N, 2° E). Plots such as these are used routinely to monitor the quality of radiosonde observations, and in all cases it is essential to assess what part of O−B may be attributed to model error and what part to observation error. This question is usually best answered by comparing the values with those obtained at nearby stations, and in the data-rich area round Hemsby, stations over the United Kingdom or other parts of northern Europe may be used. It turns out that these stations show similar values of O−B at all levels. The r.m.s. of O−B for temperature is a little more than 1 °C and for wind it is around 3–4 m s^{-1} rising to 6 m s^{-1} at jet-stream levels. Both values are considerably

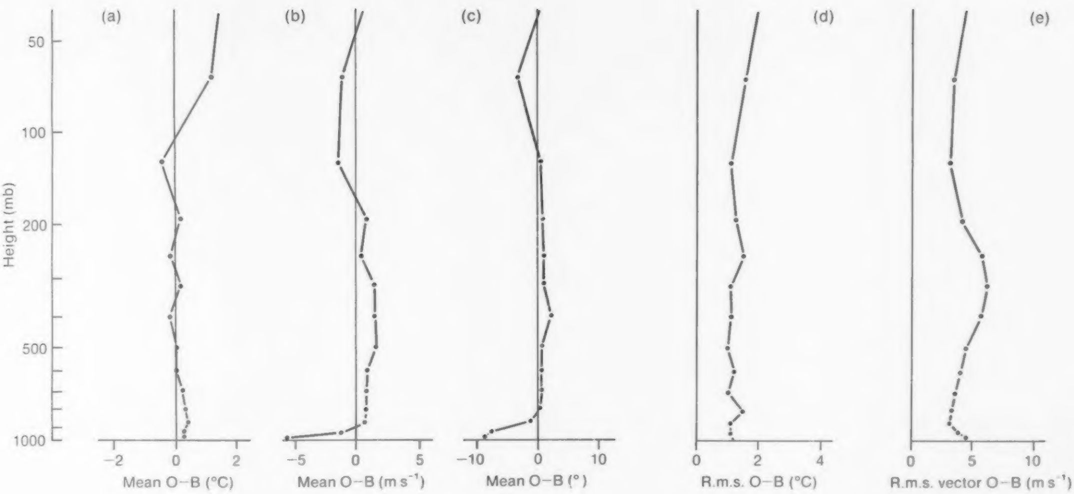

Figure 1. Vertical profiles of O—B for radiosonde observations from Hemsby (53° N, 2° E) in the period October–December 1990 for (a) mean temperature differences, (b) mean wind speed differences, (c) mean wind direction differences, (d) root-mean-square temperature differences, and (e) root-mean-square vector wind differences.

larger than the reproducibility of good quality sonde and wind-finding systems (typically 0.2 °C and 1.0 m s^{-1} respectively) and the major contributions must come from the background error (E_b) and the representativeness error (E_r). From the estimates of E_r noted in the previous section it can be seen that in an area such as northern Europe E_b is a little larger, but not by much; typical values are around 3—5 m s^{-1} for wind and 0.8—1.2 °C for temperature. The bias of O—B is mostly very small, and where there are significant departures from zero, values similar to those at Hemsby are found at all neighbouring stations. Consistent biases such as these point to regional systematic errors in the background values. There are positive O—B temperature biases of around 1 °C above 100 mb showing that the model atmosphere is too cold at these levels. There are negative speed and direction biases close to the surface which is a characteristic found at most land stations and probably reflects inadequacies of the surface processes in the model. The positive speed biases, which are largest in the upper troposphere, are another characteristic found at many middle-latitude stations and shows up most noticeably as a tendency of the model to underestimate the strength of jet streams. Apart from the biases in O—B noted above due to systematic errors of the model, the mean differences from background are small; less than 0.2 °C for temperature, 0.5 m s^{-1} for speed and 2° for direction. The largest values of the r.m.s. vector wind differences are at around 300 mb and are associated with large random model errors within the jet stream and with the strong horizontal wind shears often observed at this level which are beyond the resolution of the model. Consequently the height of this maximum varies with latitude and season in the same way as the level of the jet stream. Where comparisons are required between stations at different latitudes or between statistics in different seasons, it is usually advisable to average the r.m.s. vertically through a deep layer of the upper atmosphere. In this way dependence on the height of the jet-stream maximum is largely avoided.

Time sequences of values of O—B from a single station provide a sensitive test of quality as the paper by Hall *et al.* showed for marine observations. Fig. 2 shows a sequence of monthly mean values of O—B for 100 mb geopotential height at Hemsby over the period September 1989–August 1990. Observations at 00 UTC only have been selected to avoid the complicating effects of solar

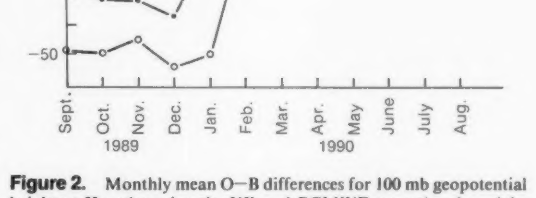

Figure 2. Monthly mean O—B differences for 100 mb geopotential height at Hemsby using the UK and ECMWF operational models. 00 UTC data only.

radiation. For comparison, monitoring values using the ECMWF model are also shown. The backgrounds from both models indicate that a change of bias occurred after January 1990, coinciding closely with the replacement of the Mk. 3 sonde by the Vaisala RS80 at that station on the 23rd of the month. The known tendency for the Mk. 3 to measure too cold is clearly evident as is a 15–20 m systematic difference between the background values from the two models.

The RS80 has now become the most widely used sonde over Western Europe and this allows an intercomparison of O—B statistics for a common instrument to be made over a large region. In Fig. 3 the mean and standard deviation of O—B temperature differences at all stations where it is operational are plotted for the period October–December 1990 using 00 UTC observations only. The values, in tenths °C, represent vertical averages performed over a deep layer of the atmosphere from 850 to 100 mb. To avoid individual observations, differing from background by a very large amount, distorting the sample characteristics, values of O—B have only been included for those observations passing the automatic quality-control checks. In practice very few observations are excluded as quality-control flags are generally raised on less than 1% of the occasions. Mean O—B lies between 0.0 and +0.3 °C at most stations, but there are exceptions principally over Spain and Italy where the mean differences are larger. The larger positive values can almost certainly be attributed to the different radiation correction schemes in operational use. Most stations (indicated by the closed circles at the station position in Fig. 3) use Vaisala '1986' corrections based on an evaluation by Vaisala of results of the WMO International Radiosonde Intercomparisons. A few stations still use earlier '1982' corrections (indicated by open circles) and in almost all cases they are the ones showing the larger mean temperature differences. The sign and magnitude of the difference agrees closely with the difference between the correction schemes at zero solar elevation (Kitchin 1989a). The second set of values in Fig. 3 gives the standard deviation of O—B temperature averaged over the layer and it can be seen that it varies smoothly over the region, confirming the uniform pattern from station to station. As noted earlier, the values, lying between 1.1 and 1.5 °C, principally represent the contributions from E_r and E_b. They are a little larger in the west than in the east, but this is to be expected as background errors are likely to show a similar regional variation rising to a maximum over the data-sparse Atlantic.

Where there is a good coverage of stations providing reasonably accurate observations, as was the case above, values of r.m.s. O—B are found to vary smoothly over the whole region. Stations with a large observation error stand out as having values which are larger than at neighbouring stations. Fig. 4 shows vertically averaged values of r.m.s. O—B differences of the vector wind

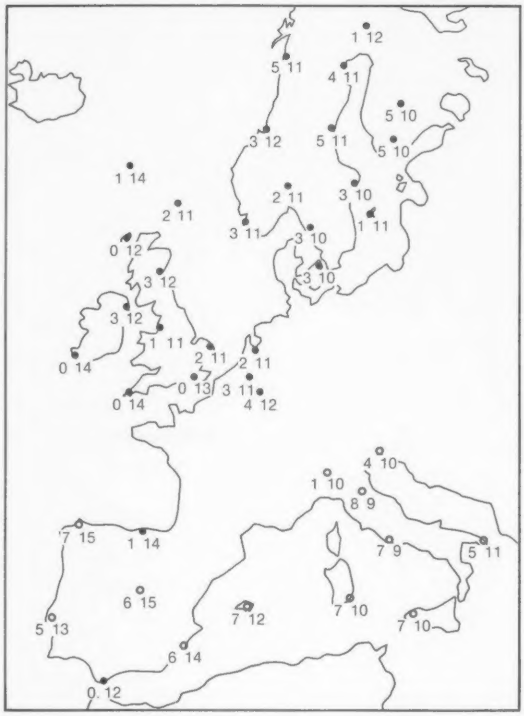

Figure 3. Mean (plotted on the left) and standard deviation (right) of O—B temperature differences at radiosonde stations using the Vaisala RS80 sonde. Values in tenths °C for the period October–December 1990 have been averaged over the layer 850–100 mb. Stations applying the '1982' corrections are marked by an open circle.

in units of tenths m s^{-1} in a data-rich region for the 12-month period January–December 1988. The vertical averaging has been performed over the layer 400–150 mb in order to obtain a representative value through the depth of the jet stream. As in the case above there is an underlying smooth variation over the region and values lie within the range 4–5 m s^{-1}, but this time three stations, identified by the letters A, B and C, stand out with values which are considerably larger than the local average. Large observation errors at these stations are the only reasonable explanation for the large differences from background.

The methods described above are valuable for identifying unreliable stations, but they do not provide much information on the nature of the problems. A more detailed study of O—B differences can reveal much more useful information, especially if it is based on a knowledge of the likely sources of error in the instrumental system in use. Three such examples are presented in sections below.

3.1 Wind direction errors

One type of wind error that is easiest to identify comes from a misalignment of the direction of true north, and

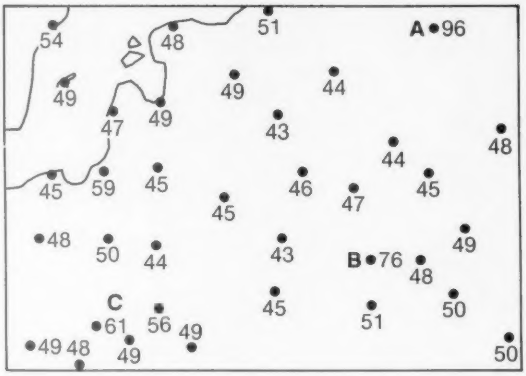

Figure 4. Root-mean-square O—B vector wind differences for radiosonde stations in the period January–December 1988. Values, in tenths m s^{-1}, have been averaged over the layer 400–150 mb. Lettered stations are referred to in later diagrams.

it shows up as a bias in wind direction relative to background and nearby stations which is constant with height. Two of the stations (A and C) identified in Fig. 4 as having abnormally large observation error are found to have a clear direction bias as Fig. 5 demonstrates. In each case the vertical profile of O—B direction differences have been plotted for the station in question and its nearest neighbour. In both cases there is a systematic difference between the pair of profiles: relative to the local average the reported directions are backed by 17° at station A and by 10° at station C. It is interesting to note that at all stations in the region there are negative direction biases in the boundary layer similar to the bias noted at Hemsby (Fig. 1). There are around 20 stations worldwide having O—B direction biases in excess of 10° which can confidently be attributed to observation error, and at least another 20 where the O—B bias is smaller and observation error is considered probable.

3.2 Wind-error dependence on balloon elevation

At some stations abnormally large observation errors occur in strong winds at the level of the jet stream. To understand why, some knowledge of wind-finding systems is required. There are three types in widespread operational use:

(a) Primary radar which measures elevation, azimuth and slant range provides, in general, the most accurate wind finding. Tests made at Beaufort Park, where a balloon was tracked by two independent radars (Edge *et al.* 1986), have demonstrated that the reproducibility of wind measurements from the UK operational radar using 1-minute averaging was better than 1 m s^{-1} r.m.s. vector error at slant ranges less than 60 km, and about 1.5 m s^{-1} r.m.s. vector error at slant ranges of 90 km.

(b) NAVAID (navigation aids) is the general term applied to systems for determining horizontal location at any point on the globe through the use of electromagnetic waves in the radio frequencies. Synchronized signals are transmitted from a number of well-spaced stations, and differences in the time of receipt at a sensor enable its position to be determined. Omega is the NAVAID system in most widespread use and achieves an accuracy of 1–2 m s^{-1} for 2-minute averages on most occasions. Loran systems are in use at some UK stations which achieve a somewhat greater accuracy.

(c) Radiotheodolite is the most common wind-finding system in use today. Radio signals from the sonde are tracked by direction-finding antennas at the ground station enabling azimuth and elevation to be measured. The height is usually determined by integrating the hydrostatic equation using the measurements of temperature, humidity and pressure in the same way as in NAVAID systems. At high balloon elevations and short slant ranges the accuracy obtained from radiotheodolites is comparable to the accuracy of NAVAID winds. However, at low balloon elevations, which are frequently encountered in the strong jet streams in middle latitudes, the reported wind is much more sensitive to errors in the measured elevation. At some stations the operational practice is that winds are not reported where the elevation falls below some critical value. At other stations secondary radar or transponder systems are used to provide direct measurements of the slant range used in the wind finding, eliminating the dependence of the derived wind on measurements of balloon elevation. Both practices lead to a reduction in the largest errors associated with radiotheodolite systems.

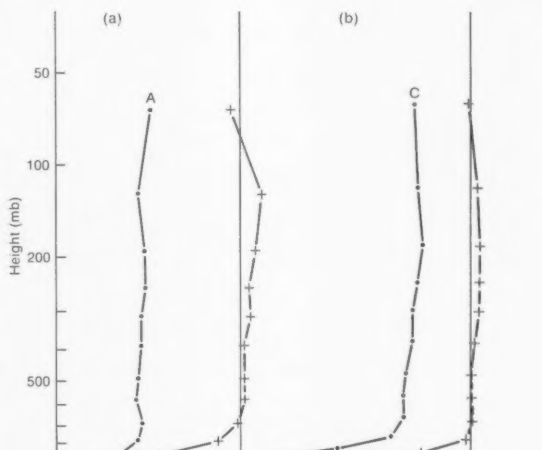

Figure 5. Mean O–B direction differences in the period January–December 1988 at (a) station A and its nearest neighbour in Fig. 4, and (b) station C and its nearest neighbour.

The problems of wind measurement at low balloon elevations at stations using radiotheodolite equipment is a major source of error in the global radiosonde network. Where there is no means of measuring the slant range, winds are calculated from measured values of balloon azimuth, elevation, and a value of the height derived from the pressure–temperature profile from the sonde. If the balloon encounters a strong jet it may be carried 100 km or more downwind and its elevation at the ground station will be less than 10°. Accurate wind measurements require an accurate measurement of the balloon elevation which is critically dependent on the precise alignment of the receiving antenna. Where misalignment occurs, errors are likely to be much larger in the component of wind along the line of sight to the balloon than in the component perpendicular to the line of sight.

The characteristics of radiotheodolite systems at different balloon elevations can be investigated using model background values. It is necessary to work in wind components which lie along the line connecting the balloon and the station (*a*-component) and perpendicular to that line (*p*-component). Differences from background for each of these components can be calculated at various balloon elevations. The balloon downwind range can be estimated from the observed wind profile given in the radiosonde report, and the height can be calculated assuming a constant rate of ascent (taken to be 5 m s^{-1} here). Of course it is not known how model errors in the *a*- and *p*-components of wind differ; for small elevations they are both likely to be larger than average as low balloon elevations result from strong winds at jet-stream level where it is known that model and representativeness errors are large. In addition, the magnitude of model errors at low balloon elevation may depend on location; low elevation implies the existence of a strong (usually westerly) jet, which in turn implies the rapid propogation of errors. In such cases, model errors on the western coasts of continents, just downwind from data-sparse oceans, are likely to be larger than at sites further inland. These model characteristics are impossible to quantify without working from observational results and, as before, background plus representativeness errors will be estimated by reference to wind-finding systems of known high quality.

Fig. 6 shows the dependence on the balloon elevation of the mean and r.m.s. O—B differences for the *a*- and *p*-components of wind. The closed circles represent values from a wide selection of stations in Europe providing observations of good quality from either radar or NAVAID wind-finding systems. All observations have been included with the exception of those making an exceptionally large contribution to the variance of O—B. These outliers have been identified using standard statistical techniques on each sample of observations having values of the elevation within a specified range. In practice far fewer observations are eliminated than have flags raised by the routine quality-control checks. All reports (TEMP and PILOT) received in 1988 have been used and vertical averages have been performed over the band 400–150 mb which includes the jet-stream maxima in most latitudes and seasons. As anticipated there is indeed an increase in O—B differences with smaller values of elevation, and the increase is a little greater in the *a*-component than in the *p*-component. These values provide a standard against which other stations may be compared. The crosses in Fig. 6 are for station B which in Fig. 4 had r.m.s. differences from background considerably larger than at neighbouring stations. It is immediately clear that the suspected observation error is contained in the *a*-component; the r.m.s. O—B of this component becomes very large at low balloon elevations, while that of the *p*-component differs little from the standard. At some stations observations cease where the elevation falls below some critical level, no doubt as a result of the local observing practice. Where observations continue at elevations below 10°, massive r.m.s. O—B differences may be found as the third example in Fig. 6 shows (indicated by the open circles) which is for a station in Asia.

The only reasonable explanation of the characteristics shown in these examples is an error in the radiotheodolite wind-finding systems in use at these two stations. In both cases the mean O—B of the *a*-component is also large and accounts for much of the variance. Quite possibly there is some misalignment of the antennas at these stations resulting in a constant bias in the measured elevation.

3.3 Errors in the assignment of height

The level assigned to a radiosonde observation, reported as a pressure in a TEMP report, may be derived in a number of different ways depending on the instrumentation: the pressure sensor on a sonde gives a direct measurement of the pressure level; alternatively the height in metres, derived from the slant range and balloon elevation, may be converted to a pressure level by applying the hydrostatic equation to the virtual temperature profile measured by the sonde. For systems with range-finding radar and a sonde with a pressure sensor, these two independent estimates of the height may be obtained and cross checked, providing probably the most accurate values of observation level. For systems with a sonde providing pressure and temperature but with no range finding, for example NAVAID and radiotheodolites without secondary radar, the pressure level assigned to the observations is simply the value measured by the sonde.

Some systems have no pressure sensor and rely on the range and elevation provided by the wind finding, and the virtual temperature profile provided by the sonde to give the pressure level. In some cases the elevation is measured by radiotheodolite and, as in the case of wind observations, errors can arise through misalignment of the instrument.

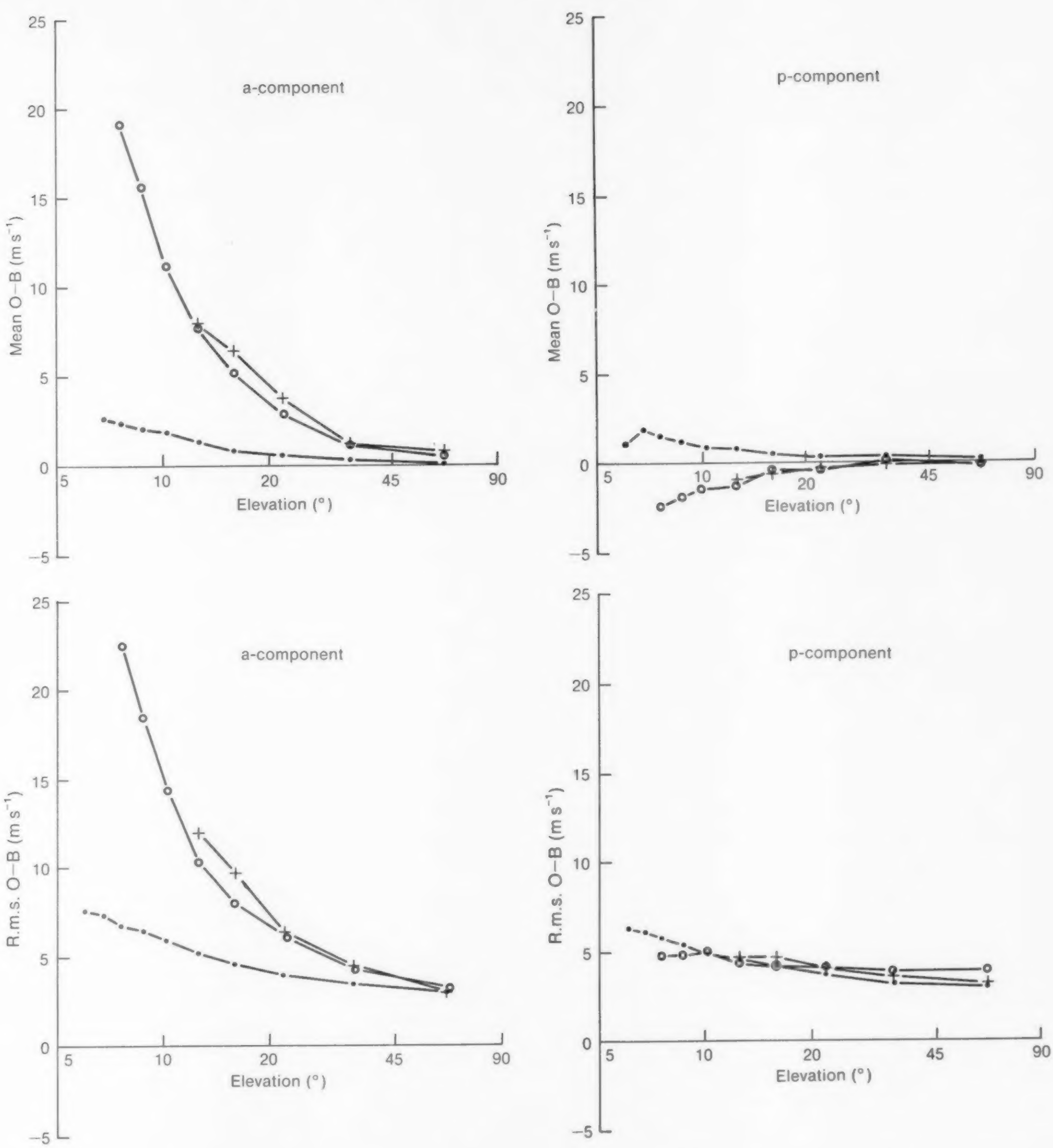

Figure 6. Mean and root-mean-square O–B differences for the wind components across (*a*-component) and perpendicular to (*p*-component) the line of sight to the balloon at various balloon elevations. Values have been averaged over the layer 400–150 mb for the period January–December 1988. The closed circles are for radiosonde stations in Europe using NAVAID or radar wind-finding systems, the crosses for station B in Fig. 4, and open circles for another station appearing to have large wind errors.

A possible way of detecting systematic biases in the height assignment is through an examination of the characteristics of the O—B temperature differences from the sonde and two examples are given in Fig. 7. Both cases are characterized by a sharp discontinuity in the profile of mean O—B at the level of the tropopause. At station D, O—B increases steadily from zero near the surface to a large negative values around 300–400 mb before falling suddenly to values much closer to zero at higher levels. Station E shows a similar profile of O—B temperature differences, but of opposite sign. Neighbouring stations show no such characteristics. It is difficult to imagine how a defect in the temperature element could result in this sudden change with height unless it has a quite exceptionally long response-time. More probable is a bias in the assignment of height which is largest at high levels. In the near-isothermal stratosphere errors in height will not lead to a temperature bias, but just below the tropopause the +3 °C bias implies a systematic error in the height of perhaps as much as +500 m.

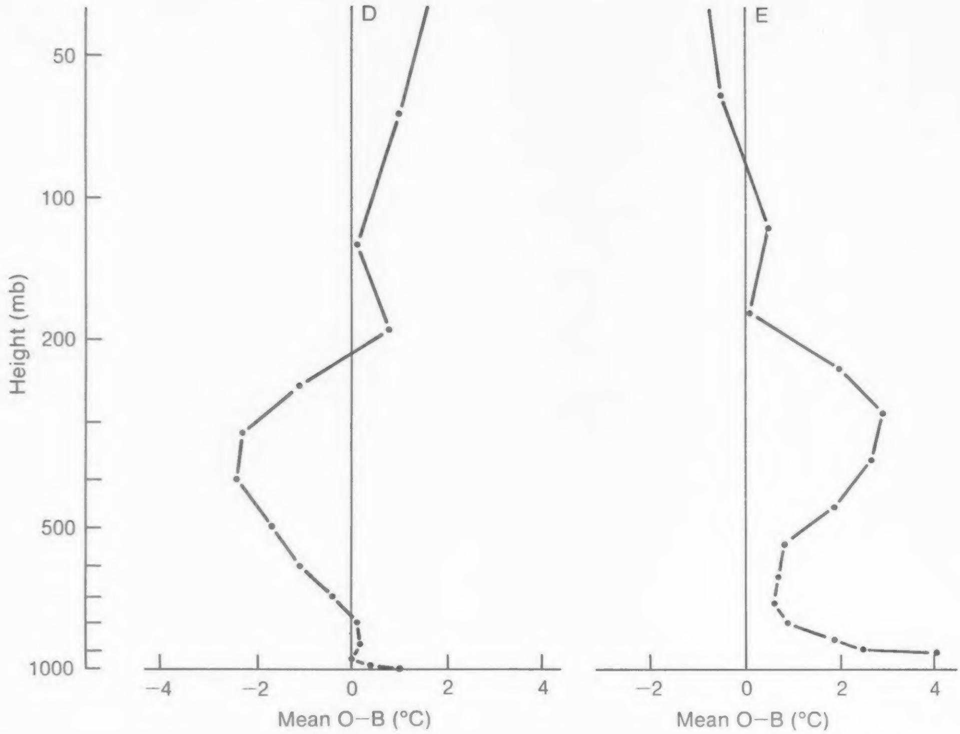

Figure 7. Vertical profiles of the mean O—B temperature differences at two radiosonde stations (D and E) for the period October 1990–March 1991.

Fig. 8 shows the mean and standard deviation of O—B temperature differences at 400 mb for different balloon elevations over the winter period October 1990–March 1991. A very marked relationship is immediately apparent; at both stations the large biases in O—B found at this level occur almost solely at low balloon elevations. In strong winds where the balloon is between 10 and 20° above the horizon the magnitude of the temperature errors is between 4 and 6°. For comparison, values for Hemsby are also plotted. In all cases the standard deviation of O—B is around 1.0–1.5 °C at high evelations rising to 2.0–3.0 °C where the elevation is below 20°. Larger random errors in the background values are to be expected at low balloon elevations, which are indicative of a changeable synoptic type. It is apparent that a systematic bias in the observations accounts for most of the variance of O—B.

According to information provided to WMO, there is no pressure sensor on the sonde at these two stations, and the observation level is obtained from the slant range provided by the secondary radar, the balloon elevation provided by the radiotheodolite, and the temperature profile provided by the sonde. The most likely explanation of the error detected at these two stations is a systematic error in the measured balloon elevation, due no doubt to a misalignment of the antenna of the radiotheodolite system.

4. Concluding remarks

Background values from high-resolution numerical models provide a powerful means of monitoring the quality of observations. Three components contribute to the differences between observations and background: measurement errors, background errors and representativeness errors. For reliable operational radiosonde systems measurement errors are the smallest contribution. Where the observations are of poor quality the measurement error may make up a large part of O—B, and this may be detected through routine monitoring over a period of time. The accuracy of the background is a limiting factor in the success of the monitoring method, and results must be presented in the context of estimates of the background error. The results in this paper seem to provide justification for the assumption that background errors averaged over long periods of time vary only slowly in space. This is critical for identifying stations with larger than average measurement errors. In general, r.m.s. O—B values have uniformly low values highlighting the reliability of the observations, but a few stations stand out with values significantly larger than others in the immediate neighbourhood. Where this is the case, observation error is the prime suspect.

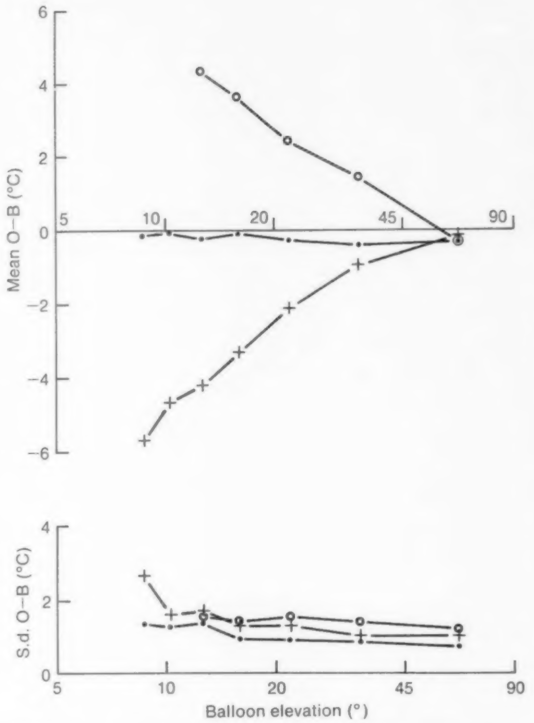

Figure 8. Mean and standard deviation of O–B 400 mb temperature differences at various balloon elevations for the period October 1990–March 1991. The closed circles are for Hemsby, and the crosses and open circles for stations D and E respectively of Fig. 7.

Background values also provide a useful tool for investigating the cause of some of the errors. A number of techniques have been outlined here and no doubt more could be developed. Direction biases in the reported wind, due presumably to the misalignment of true north, are surprisingly common and seem to be a major source of error at some 20 or more stations worldwide. Even more common are problems with radiotheodolite systems where the measurement of wind or pressure level depends critically on the balloon elevation. Large errors have been noted in the examples provided here, and there are many other stations where the errors are equally as large. In many cases the error can be attributed to a systematic bias in the measured elevation, pointing to a levelling problem with the antenna of the instrument.

The methods outlined here provide a basis for the regular monitoring of observations worldwide. Recognizing this, WMO established lead centres for the monitoring of different types of observations. Since 1987 ECMWF has been lead centre for radiosonde data, co-ordinating all results of quality evaluation, and providing those making the observations with monitoring information relating to their station. The information presented here is also of great value for improving the use of observations by the numerical forecast models; estimates of the observation error at each station can be used to give more reliable weights to the observations within data assimilation, and some of the more obvious biases can be corrected. An essential requirement of all these applications of monitoring results is a continual updating of the monitoring information.

Acknowledgements

The author would like to thank John Ashcroft and Jonathan Wright for their help in developing the computer programs needed to provide the results presented here, Alan Radford for providing the ECMWF monitoring results for Hemsby, and John Nash for his helpful comments on the text.

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Meteorological and hydrographical aspects of the Battle of Copenhagen, 2 April 1801

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Summary

Following diplomatic conflicts between Britain and Russia, on 18 November 1800 the tsar imposed an embargo on British ships in Russian ports. In practice this meant a ban on British ships in all Baltic ports, including the ports from where Britain used to obtain an important fraction of her grain imports (45% in 1800). Toward the end of November, the British Cabinet decided to send a fleet to the Baltic, as soon as ice conditions of that sea permitted, to break the embargo. The plan of naval action against Russia was extended in January 1801 to the navies of the other states of northern Europe when Britain learned that they entered into an Armed Neutrality Pact with Russia. The sequence of the attacks was based on climate.

The winter of 1800/01 was a mild winter in the Baltic region which made it possible for the British fleet to sail on 12 March 1801. The fleet's Second-in-Command was Nelson who formulated the plan of attack on the Danish navy (the first to be attacked) arrayed in defensive positions along Copenhagen's coast. The plan leaned heavily on winds. The battle took place on 2 April and ended in British victory.

The paper makes use of data of Copenhagen's meteorological station of the time (pressure, wind, temperature and weather) as well as on the wind records of two British and one Danish warship.

1. Introduction

In the two successive years 1799 and 1800 the British Isles suffered from crop failure. The winter of 1798/99 was cold, the spring and summer of 1799 cool and rainy, with the consequence that the wheat harvest was down by 50%. The weather characteristics of 1800 were nearly opposite — the spring and summer were warm and rather dry, and in the London area no rain fell in June. The Azores anticyclone extended well into western Europe for weeks. The failure of the 1800 wheat crop was but 25% but, since no reserves were left, the scarcity of bread became even graver and prices rose.

The scarcity led to numerous bread riots, some of them violent and destructive. Among others, such slogans appeared as 'Peace and Large Bread, or a King without a Head'. The memory of the French revolution was still fresh. And, in view of the renewed crop failure, the prospects of still more violent bread riots and danger to the public order during the coming dearth year became even more alarming.

In 1800 the British Isles were able to obtain 45% of their grain imports (wheat, barley, oats, rye, beans and peas) from Baltic ports. But, on 18 November 1800 (NS), the tsar, Paul I, imposed an embargo on British ships in Russian ports and, since the countries around the Baltic were under the tsar's domination, the Russian embargo meant the exclusion of British vessels from all Baltic ports. The loss of these imports portended an even graver scarcity in Britain in 1801. Apparently, on 28 November (1800) the British Cabinet decided on a naval attack on the Russian fleet in the Baltic, as soon as ice conditions permitted sailing, to break the embargo. Soon after mid December the tsar succeeded in bringing together all the countries of northern Europe (Denmark, Prussia and Sweden) to join his empire in an Armed Neutrality Pact which would have entailed armed resistance against the British claim of her right, as a belligerent, of searching neutral vessels for contraband of war (war against France). When the signing of the Pact became known in London in January, this gave additional weight to the earlier decision to go against Russia, but now the plan of attack included all signatories of the Pact. The northern neutrals, especially Denmark, which had a relatively large merchant navy, were called upon to abandon the contract or face the consequences.

The weather conditions of 1799 and 1800 in the British Isles and in some of the grain-growing areas of Europe, the consequences on the harvests, the bread riots in Britain, etc. are described in Neumann and Kington (1992). The diplomatic conflict between Britain, on the one hand, Russia and the other north-European powers, on the other, is described in a book by Pope (1972). Pope also describes the events of the sailing of the (British) 'Baltic fleet' and, especially, the course of the Battle of Copenhagen and its sequels. In an English-language book, the Danish historian Feldbæk (1980) discusses the diplomatic conflict and, in a subsequent book in Danish, he describes (Feldbæk 1985) the events and course of the battle.

2. Climate governs British naval strategy

Referring to the planned naval war in the north, Dudley Pope makes the statement in his book *The Great Gamble* (1972, p. 125) that 'climate governed British naval strategy and planning for the Baltic'. The jacket of the book adds the subtitle 'Nelson in Copenhagen'; the term 'gamble' implies the possibility of failure because the Danish navy represented a strong force.

The plan of attacks on the navies of the northern neutrals is laid out in a memorandum, dated 5 February 1801, submitted to the Admiralty by Vice-Admiral Nicholas Tomlinson (ret.), see *The Tomlinson Papers* (1935, pp. 299–305). Tomlinson saw service previously with the Russian navy on behalf of Britain and, thus, he had personal knowledge and experience of the tsar's Baltic fleet, its bases at Kronstadt (St Petersburg) and Reval (Tallinn) in the Gulf of Finland and the way the fleet is set into operation after its hibernation in winter locked into ice.

Tomlinson's proposal was to attack the Danish navy first, as soon as the ice thawed in the Danish water, and before the ice melted in the Gulf of Finland. In such a case the Russian fleet in the Baltic would not be able to come to the aid of the Danes. He goes on pointing out that the ice at Kronstadt usually thaws 7–10 days later than at Reval and then, assuming the the Danish navy had already been put out of operation, neither the Danish nor the Kronstadt-based warships could help the ships at Reval. Finally, after the presumed defeat of the fleets at Copenhagen and Reval, the British fleet could deal with the fleet at Kronstadt. (We do not know if the Admiralty developed a similar climate-based plan, independently of Tomlinson.)

The figures quoted by Tomlinson for the difference in thawing at the two Russian bases, are in fair agreement with modern data, see Fig. 1.20 in the paper *Physical features of the Baltic Sea* by Mälkki and Tamsalu (1985).

3. The winter 1800–01 in the Baltic

The proviso 'ice conditions in the Baltic permitting', or variants of this phrase, are recurring features of documents of the Cabinet (e.g. in a letter of Henry Dundas, Secretary of State for War, to the Admiralty; reprinted in Clarke and M'Arthur (1859, p. 259) and letters or orders of the Admiralty (see, for example, letter of the Admiralty to Sir Hyde Parker; reprinted in *The Nelson Papers*, 1845, p. 295). Apparently, it was not before the middle of February 1801 that the fact of mildness of the winter in the Baltic became known in London. (The winter was also mild in the British Isles, see Table I below.) The first published indication of the light winter in northern Europe was printed on p. 2 in the issue of *The Times* for 14 February. According to a short report from Memel, a harbour city on the south coast of the Baltic (then part of Prussia, now in Lithuania under the name Klaipeda), dated 10 January, 'the weather is so mild that our harbour has 16 fathoms at the entrance'. The qualification 'the weather is so mild' makes it unlikely that the high water level was due to strong onshore winds. One plausible reason for the high level was a late freezing of the rivers emptying into the sea. Another report of mildness appeared on 20 March in the Copenhagen newspaper *Kjøbenhavnske Tidende*. The news item, dated 3 March, Stockholm, reads as follows in translation: 'The extremely mild weather has favoured the rearmament of the navy. The Åland Sea has been reportedly ice-free'. The Åland Sea is the area of the Baltic sea between Uppsala and the south-west corner of Finland. Lt Col William Stewart, Commanding Officer of the land troops attached to the 'Baltic fleet', writes in his narrative of the Battle of Copenhagen that [in March 1801] 'the openness of those seas had rarely been equalled at this season of the year'. The narrative is reprinted in *The Nelson Papers* (1845, see especially p. 300). His narrative will be mentioned again below.

In Table I are listed the air-temperature data of Copenhagen, Riga and Stockholm, as well as of Central England for late autumn, winter and early spring 1798–99 to 1802–03. The data bring out the fact that the winter of 1800/01 was mild, especially in comparison with winter of 1798/99. The difference between the two winters is even more clearly brought out by the number of days during which the Danish Sound (Sound, for short) was ice-bound in 1798–1803, see Table II. To the

Table I. Mean temperatures (°C) of the months November–March 1798–99 to 1802–03 at stations of the Baltic region, with parallel data of Central England for comparison (World weather records (1927), Wild (1881), Manley (1974)

Years	Copenhagen	Riga	Stockholm	C. England
1798–99	−1.7	−7.6	(−4.0)	2.8
1799–1800	−1.0	−4.0	−4.4	3.2
1800–01	2.6	−1.0	−0.9	5.0
1801–02	−0.4	−1.4	−1.8	3.4
1802–03	1.9	−6.5	−4.0	4.4
1931–60	1.9	−2.6	−0.8	4.9

Table II. Ice data for the Danish Sound, Riga and the Baltic as a whole, 1799–1803. The year date is that of the year into which January falls (Lamb 1977).

	1799	1800	1801	1802	1803
Number of days that the Sound was ice-bound	135	109	0	11	60
Date of final opening of Riga's port for shipping (number of days since 1 January)	107	102	85	79	96
Maximum extent of ice cover of the Baltic, in 1000 km^2	420	400	136	220	400

table have been added the dates of opening of Riga's harbour to shipping in spring, and figures on the greatest extent of ice cover of the Baltic in the same years. All three sets of data are listed in Lamb (1977, pp. 587–589). The figures are particularly relevant to the planned attack.

In 1801 the ice cover of the Neva at St Petersburg broke up on 17 April (NS; see Rykatschew (1887), p. 171), the average date for the recent decades being between 21 April and 1 May (Mälkki and Tamsalu, 1985, Fig. 1.20). As to Reval, the other Russian naval base in the Baltic of the time, a letter dated 30 June 1990 of Dr Andres Tarand (Botanical Gardens, Tallinn) states that the port of Reval became ice-free, according to the State Archives at Tartu (Dorpat) on 1 April OS, which could be either 12 or 13 April NS. The latter dates are very close to the date of the break-up of the ice cover at Tallinn in recent decades. It is reasonable to assume that the date of the 'break-up of ice cover', as used by Mälkki and Tamsalu, occurs a few days before the port becomes 'ice-free', the term adopted in the Estonian record. If this assumption is correct, then the break-up at Reval took place, as we would have expected, earlier than the average date in recent decades.

In view of the reports of a mild winter in the Baltic, the Admiralty issued orders on 11 March for the (British) 'Baltic fleet' assembled at Yarmouth, to set sail. The fleet consisted of just over 50 sail, including 16 (later 17) sail-of-the-line. The Commander-in-Chief of the fleet was Admiral Sir Hyde Parker, with Nelson as Second-in-Command. With the fleet went some 800 land troops, commanded by Lt Col William Stewart of the Rifle Battalion (mentioned earlier).

The voyage in the North Sea was rough. On the 15th (March), a south-west gale dispersed the fleet, but the ships reunited on the 19th off Skagen (The Skaw for the British of the time), the northernmost extremity of Jutland. In a letter of the 16th, Nelson complained that 'our weather is very cold, we have received much snow and sharp frost' (*The Nelson Papers*, 1845, p. 294).

4. Winds in the Danish waters: The Kattegat and the Sound

A wind from the north-west was needed to reach Copenhagen from Skagen. Such a wind blew for a few days from the 19th on, but Parker delayed moving toward Copenhagen. Nelson was irritated by the delay for he wanted to deny the Danes additional time for strengthening their defences. On the 24th, after a journey of some 230 km, the fleet anchored at a point close to Elsinore with its Kronborg Castle or fort, that guarded the entrance to the Sound where this was at its narrowest, that is 4 km. (The fort is the supposed scene of Shakespeare's play *Hamlet, The Prince of Denmark*.) At that point, north-west of Elsinore, a rendezvous was fixed with a British diplomatic delegation to Copenhagen, which tried in vain to persuade the Danish authorities to abandon the Armed Neutrality Pact, or the Danish navy would be attacked. The diplomats also spoke of the intense preparations and heavy defence works at the capital.

It seems that the fleet was favoured by the occurrence of north-west winds between the 19th and the 24th, as mentioned above. This follows from a comparison with wind-direction frequencies of the recent decades. Frequencies, as observed at the rather open site of the sea fort Trekroner (3K in Fig. 1), built on a shoal some 700 m from Copenhagen's coast, are summarized by Lysgaard (1969, pp. 9–10). His tables are based on eight observations a day in the years 1931–60. The data from

Table III. Frequency distribution, in %, of wind direction at the open site of the entrance from the north to the Copenhagen Roads section of the Sound (Lysgaard 1969)

Month	N	NE	E	SE	S	SW	W	NW	Calm
March	8.6	9.0	14.0	15.3	8.1	10.2	16.4	11.8	6.6
April	8.3	6.5	9.8	13.3	11.1	12.6	16.9	12.8	8.7

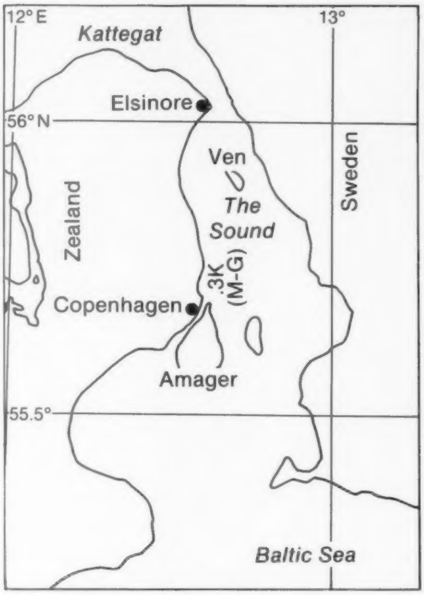

Figure 1. Map of area of the Danish Sound. Kronborg Castle is situated on a tongue of land jutting out from Elsinore (Helsingør in Danish). The symbol 3K stands for Trekroner (= Three Crowns, also called Crown Island by the British). (M-G) indicates the position of the top layer of a major shoal (about 3 km long and 1½ km wide), covered by a shallow layer of water. Copenhagen Roads or Roadstead is on the west side of the shoal. Trekroner was the largest of the sea forts guarding the approaches to Copenhagen. The scale of the map follows from the fact that at Copenhagen's latitude the distance between two longitude lines 1° apart is close to 60 km.

March and April are listed in Table III. The table shows that northerly winds are, on the average, much less frequent than southerlies.

A reference to the pressure and wind observations of the time at the meteorological station on the 'Round Tower' (36 m above street level), in what is now the Old City of the Danish capital, suggests the passage of two high-pressure systems which produced two spells of north-west winds with little time in-between for winds from the south, see Fig. 2. Presumably, the col passed at night between the observations at 21 LST and the observations at 07 LST the next morning, 31 March–1 April.

5. Currents in the Kattegat and the Sound

The currents in these two sea areas are predominantly north-west to northgoing, even when the wind is from the north, excepting the cases of strong winds from the north.

Table IV. Directions of currents in the Sound, 1931–60 (Nielsen 1976)

Sea area	Direction	% of time
In the north	From the SSE	67
(Lappegrunden fire ship)	From the NNW	32
	Other directions	0
	Calm	1
In the south	From SW	59
(Drogden fire ship)	From the NE	36
	Other directions	1
	Calm	4

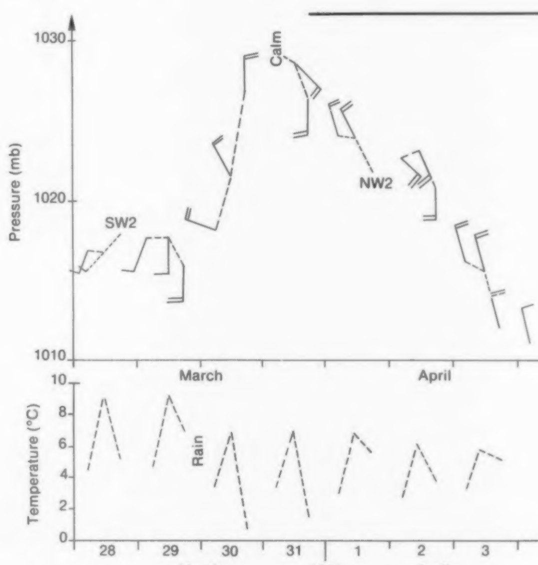

Figure 2. Pressure, wind, temperature (and some weather) data from the meteorological station situated near the top of the Round Tower of Copenhagen, 36 m above street level. The observations were taken at 0700, 1200, and 2100 LST. The wind-force scale used at the time was on the scale of 0 to 4: 'Force' 0 = 0–0.8 m s^{-1}, force 1 (one barb) = 0.9–4.3 m s^{-1} and force 2 (two barbs) = 4.4–9.2 m s^{-1}. The weather was mainly cloudy. Rain fell during the night of 29/30 March, when a cold front passed the Sound, as indicated by the typical wind shift and drop in temperature. Note the wind calm about the time of the highest pressure. The dashed lines connect the time-points of the three observations of the day. In two cases the direction of wind coincides with the dashed line. In these cases, the wind direction and force are indicated by letters and numerals.

Table IV lists the directions of currents in the Sound in 1931–60 (Nielsen 1976, p. 29). The high percentage of northgoing currents is due to the fact that in the Baltic the sum of freshwater inflow and precipitation greatly exceeds evaporation. According to Mikulski and Falkenmark (1986, p. 121), the main items of the annual water balance of the Baltic in 1931–50 were as follows: river inflow 436 km^3, precipitation 250 km^3 — or a total of 686 km^3; evaporation 250 km^3. That is, the sum of the first two is nearly three times as great as the third. Since the only outlet of the Baltic is the North Sea, the flow of surplus waters is to the north-west to north in the Great Belt and the Sound.

Dietrich (1951, pp. 130–131) publishes a table of vectorial velocity of the current in the Sound. For 1901–30 he gives a vectorial velocity of 0.92 knots in March and 0.77 knots in April in the north of the Sound (Lappegrunden fire ship) and, respectively, 0.11 and 0.18 knots in the south (Drogen fire ship). All these vectorial velocities are directed northward. As could be expected, the velocities are higher in the narrow north. In his Table II, Dietrich reports maximum velocities of northgoing currents of 3.6 knots in the north, and 3 knots in the south.

The occasional high current velocities in the north make it likely that the Baltic fleet may have encountered strong northgoing currents on its approach to the Sound. As examples for the disturbing effects of the northward current on the movement of the British fleet in the Sound and the waters on the way to the Sound, two cases are cited. On 27 March, the fleet was virtually immobilized at an approximate distance of 15 km north-west of Elsinore, on account of strong south-south-westerly winds; on the 28th, the wind veered west for some hours and Parker ordered the fleet to weigh anchor but found that 'the ships would not steer owing to a counter-current' (Pope (1972) p. 296, quoting the Admiral's diary). In fact, the fleet was swept northward and Parker had to order the fleet to anchor with Kronborg Castle in sight to the south-east. A second case occurred the day of the battle in the Copenhagen Roads (2 April) when a British frigate (*Jamaica*), with a convoy of gun-boats and other small craft, fell in with the counter-current and had to signal the Admiral that it is unable to proceed (Clarke and M'Arthur, Vol II (1859), pp. 266–267).

6. Sailing to the Sound — Copenhagen's meteorological observations and wind records of British and Danish warships

Since the orders of the Admiralty were to attack the Danish navy if their authorities refused to come to terms with the British demands, and since the Danes refused, the British fleet was to proceed to battle. There were two possible routes to Copenhagen: one was south in the Great Belt, the relatively wide (but shallow) sea area to the west of Zealand, the island on which the Danish capital was situated and then, turn north at the southern extremity of the island as soon as a suitable wind-direction change took place. The other possibility was to sail directly to the Sound by Kronborg Castle at Elsinore where the Sound is, as was mentioned above, at its narrowest. The fort was guarding the entrance to the Sound, and it was equipped with about 100 guns. The first solution was disliked by Nelson because it would have given the Danish authorities more days to advance their preparations and training. Parker, on the other hand, was alarmed by the reports of the serious defence works of the capital, and preferred the first solution.

From now on we shall make use of the data of Copenhagen's meteorological station of the time (pressure, wind, temperature and weather at 0700, 1200 and 2100 LST) as well as the wind data (mainly of direction) recorded in the original logbooks of the British sail-of-the-line *St George* and *Elephant* (the logbooks are preserved at the Public Record Office, Kew, near London), as well as of the Danish sail-of-the-line *Elefanten* (kept at the Danish State Archive, Copenhagen). The 98-gun *St George* was Nelson's flagship until 27 March when, in preparation for the battle in the shallow Sound, he shifted his flag to the lighter, shallower-draught 74-gun *Elephant*. We shall also make some use of Lt Col Stewart's account of the days before the battle and the day of the battle. We shall cite some of his wind reports and consequences of the winds on the movement of the fleet. However, as his account was written from memory, we shall take notice of some corrections put forward by Pope (1972) who studied the events of the journey and the battle on the basis of documents. In addition to Pope's detailed account, there is a detailed account in Danish in a book by Feldbæk (1985).

On the 26th in the forenoon a west wind blew for some hours. The fleet sailed a few leagues (one league equals just under 5 km) in the Great Belt when Parker ordered return to the previous anchorage. Apparently, the fact that some of the small craft hit rocks and the navigational difficulties in the shallow waters prompted him to change his mind. From the 27th to the 29th, the winds were from the south most of the time, both according to Copenhagen's data and logbooks of all the three warships, see Fig. 2 for Copenhagen's data. In the figure, the wind force is on the scale from 0 to 4, used around 1800, before the introduction of the Beaufort scale. According to information received from Dr Knud Frydendahl (Danish Meteorological Institute), 'force' 0 corresponded to a speed of 0–0.8 $m\ s^{-1}$, force 1 to 0.9–4.3 $m\ s^{-1}$ and force 2 to 4.4–9.2 $m\ s^{-1}$.

On the 29th a Council of War was held on Parker's flagship the *London*, where Nelson presented his plan for the battle which heavily leaned on winds. Before describing the plan in brief, we have to refer to Fig. 1 which shows that the west side of the Copenhagen section of the Sound is divided by a major underwater shoal, the Middle Ground, running north–south; the shoal is covered by a shallow layer of water. Nelson

proposed to take part of the fleet (Nelson's division) southward, on the east side of the shoal, at a safe distance from the Danish guns. This phase required a north wind. The division would then anchor at a point south of the shoal and, as soon as the wind blew from the south, the division would sail northward on the west side of the shoal, in the channel called King's Deep, to give battle. This roadstead, including the channel was, roughly, 1200 m wide. The Danish navy was arrayed in stationary defensive positions in two lines on the west side of the channel, close to and parallel with the Copenhagen shore line. According to Nelson's proposal, the remaining ships of the fleet, including Parker's flagship, would take up positions north of, and close to, the roadstead, and assist Nelson's division in the battle with their fire. The plan was approved, and, if we follow the printed literature (e.g. Lt Col Stewart's account), Nelson then shifted his flag from this flagship the heavy, 98-gun *St George* to the lighter and of lesser draught 74-gun *Elephant*. (According to the original logbook of the *Elephant*, the shift took place on the 27th, as mentioned above, but this discrepancy is of no meteorological relevance.)

Between the 29th and 30th a cold front passed the area, see Fig. 2. Aside from the wind shift and a drop in temperature, there was some rain during the night. On the 30th, following the passage of the front, the pressure rose sharply, north-westerly winds blew and an anticyclone travelled across. The north-westerly wind enabled the fleet to sail eastward, to a point close to 25 km from Copenhagen (near the island of Ven, made famous by the astronomer Tycho Brahe), see Fig. 1. It seems that the next night the centre of the anticyclone crossed the area. At 0700 LST, the Round Tower Observatory recorded a pressure of 1030 mb and a calm wind, see Fig. 2.

7. Winds and the Battle of Copenhagen

Copenhagen's meteorological data indicate (Fig. 2) that during the night of 31 March/1 April the wind veered to the north-west. The same is indicated by logbooks of the three warships, see Table V. The sequence of direction shifts suggests that another anticyclone, albeit with a lower central pressure, traversed the area, that is, if we assume that the travel of the system was from west to east.

In the forenoon of 1 April the whole fleet sailed with a favourable north-westerly wind to an anchorage about 9 km from Copenhagen, off the north end of the Middle Ground. While Parker's division took up positions north of Roads, the brisk north-westerly wind enabled Nelson's division to sail south on the east side of the

Table V. Winds and some weather information, as reported by Copenhagen's meteorological station and recorded in the logbooks of two British and one Danish warship. The figures on the left-hand side of each column state the hour LST. A complete copy of the entry for 2 April in the logbook of HMS *Elephant* (Nelson's flagship in the battle) is printed in a volume edited by Jackson, Vol. II, 1900, 91–92. Note that in the logbooks the day begins at noon with the date of the next day.

Date	The Round Tower station in Copengahen		HMS *St. George*		HMS *Elephant*		*Elefanten*	
	LST		LST		LST		LST	
1 April 1801	07	NNW 2; scattered skies		Moderate breezes S to NW, cloudy		SSW NW in the morning. Moderate breezes, fair	08	NW
	12	NW 2; nearly overcast					13	NW
			13	NNW. At 15.30 Nelson's division sails south on the east side of the Middle Ground. At 16.40 the division anchors south of Copenhagen				
	21	NW2; overcast			15	Nelson's division weighs anchor and sails through the east side of the Middle Ground	18	Calm
							24	Calm
					17	Division anchors south of Copenhagen		
			19, 21, 23	Light breezes, cloudy				
			24	Winds S to E				
2 April 1801	07	SE 2; overcast	13	Moderate breezes and cloudy. Engagement continues	A.M.	Fresh breezes, cloudy	01	SE
	12	SSE 2; nearly overcast			10.10	Van division sails to attack	08	ESE
	21	S 2; overcast					13	SSW
					P.M.	Moderate breezes and fair. Truce etc.	18	S to E
							22	S

shoal and anchor about 3 km from the southernmost Danish warship (but within range of a few coastal guns of the island (Amager, see Fig. 1) to the south-south-east and close by the capital.

The next morning, 2 April, another wind-direction shift took place (see Fig. 2 and/or Table V), just as required for Nelson's plan. At about 1000 LST, Nelson's division set sail northward, with an essentially southerly wind, into the roadstead between the capital's coast and the shoal. As stated earlier, in these waters were arrayed the Danish warships in stationary defence. The Danish defenders put up a resolute fire against the British attack, so much so that at 1315 or 1330 LST Parker deemed that the course of the battle did not favour the British fleet. But Nelson saw the situation differently. It was at this time that the famous incident occurred. Parker signalled Nelson to disengage, but Nelson put his telescope to his blind eye and ignored the instruction. By 1400 LST the Danish fire became sparse — it was clear that the Danish navy was defeated. At 1430 Nelson sent a flag of truce to Copenhagen.

Pope (1972), Appendix III, p. 530, summarizes the casualties of the two sides — about 1035 on the Danish side and 944 on the British side. (Pope remarks that the British losses may have been slightly larger, because some who did not report wounded, may have died later.) Nelson reported that all the Danish sail-of-the-line south of the Trekroner fort, 17 in number, were either sunk, burnt or captured. In his Appendix II, Pope (1972) lists the ships in Nelson's division that suffered damages. Of 17 ships in action, one suffered severe damage, slight to somewhat more than slight damage was inflicted on 15, and one was unharmed. An armistice of 14 weeks was agreed upon and signed by the two sides on 9–10 April.

Fig. 3 is a copy of an etching *The Battle in the Roadstead, 2 April 1801* by the Danish engraver Johan Frederik Clemens (1749–1831), made after a painting of the same title by the Danish painter Christian August Lorentzen (1746–1828). It shows the burning Danish warships. Since the ships were aligned in an approximately north–south line (north to the left), the painter shows that the smoke was drifting to the north-west. As stated earlier, the wind was from the south-east or south-south-east, see Table V.

Acknowledgments

The writer is pleased to thank Drs Knud Frydendahl and Povl Anker Skovmand, Danish Meteorological Institute, for their ready assistance with data and

Figure 3. Photographic copy of an engraving by the contemporary Danish artist Johan Frederik Clemens, after a painting by the contemporary Danish painter Christian August Lorentzen. The picture shows the burning Danish warships whose smoke drifts toward the north-west (north is to the left in the picture), in agreement with the fact that the wind of the day was south-south-east to south-east.

comments. Commander A. Holm, Librarian, Danish Marine, and his staff are thanked for naval literature, and Dr Torben Jacobsen, Technical Highschool, Lyngby, is thanked for literature on the physical oceanography of the Baltic Sea. Further thanks are due to Prof C.C. Tsacherning, Institute of Geophysics, University of Copenhagen, for the map in Fig. 1. Finally, credit is due to the Danish State Museum of Art, Copenhagen, for a copy of Johan Frederik Clemens' engraving *The Battle in the Roadstead, 2 April 1801*.

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Objectively analysed cloud immersion frequencies for the United Kingdom

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Summary

Occult deposition, the scavenging of cloud and fog droplets by the land surface and vegetation, forms a significant contribution to the total wet deposition of chemical species to the surface in elevated regions. To assess the magnitude of this contribution it is necessary to have reliable estimates of time spent in cloud on a spatial scale of that of the orography. However, direct observations of cloud immersion are grossly inadequate to define the pattern over a topographically complex area such as the United Kingdom, so use must be made of proxy data. A method is described which makes use of statistics which are routinely available to estimate cloud immersion frequencies for any given land elevation in any part of the United Kingdom. The detailed results of the analysis are obtainable from the author.

As expected, frequencies are strongly dependent on land elevation. Over Scotland at low elevations frequencies are higher in the east than in the west, due mainly to the effects of North Sea stratus, but at elevations above about 500 m frequencies are higher in the west.

1. Introduction

It has been observed by many workers that the concentrations of all major ions in cloudwater collected at elevated sites exceed those in rainwater at the same sites by factors of two or more (Fowler *et al.* 1988, Schmitt 1988, Waldman *et al.* 1985). The deposition of cloudwater to elevated regions leads to a significant contribution to the total wet deposition of chemical species to the surface, particularly if extensive vegetation is present which, together with strong winds, can lead to efficient scavenging of the cloud droplets.

The decline of elevated forests has been observed in several countries (Blank 1985, Saxena *et al.* 1989) and air pollution is suspected to be a contributing factor. Thus it is important to have information of cloud immersion frequencies so that areas which are especially prone to large occult deposition can be identified more readily.

In the United Kingdom very few meteorological observations sites are at elevations above 300 m, so that direct data of cloud immersion are very few. Moreover, the pattern of cloud immersion frequency is likely to be of a scale equal to, or smaller than, that of the orography, so that a prohibitively large number of stations would be required to define the pattern explicitly.

It is clear from the foregoing discussion that direct observations of cloud immersion are grossly inadequate to define the pattern over a topographically complex area such as the United Kingdom, so use must be made of proxy data.

2. Approach to the analysis

Under most meteorological circumstances the spatial variation of cloud-base level is relatively small. When the air below cloud base is well mixed (either because of convection or due to frictionally generated turbulence), the level of cloud base will be almost uniform — even over hills where orographic lifting of low-level air takes place. When the low-level air is thermally stable, such orographic lifting will normally lead to the level of cloud base being lower over the windward side of hills than the general level of cloud base.

A standard statistic derived from cloud observations made at meteorological stations is the percentage of time that the sky has cloud of ⅝ or more at various specific heights. At Royal Air Force stations the statistics are for ⅜ or more cloud cover. If it is assumed that elevated land is 'passive' in that it samples the cloud without either affecting the cloud-base level or the cloud amount, then data from neighbouring stations can be used to estimate cloud immersion frequencies at a site, given its height above sea level.

The fraction of time that ground in a particular location (x, y) at a particular elevation (z) is in cloud is given by

$$F(x,y,z) = \sum_{i=1}^{8} {}^{i}/_{8}\, f_i\,(x,y,z)$$

where i is the cloud cover in oktas and f_i is the fractional time that the sky is covered by i oktas of cloud at or below the particular elevation considered.

The data being used refer to the fractional time that the sky is covered by either ⅜ or ⅝ (as appropriate) of cloud or greater, given by

$$F_3(x,y,z) = \sum_{i=3}^{8} f_i\,(x,y,z) \text{ and } F_5(x,y,z) = \sum_{i=5}^{8} f_i\,(x,y,z).$$

If the frequency distribution f_i is symmetrical with respect to i, it can easily be shown that

$$F(x,y,z) = F_5(x,y,z) + \tfrac{1}{2} f_4(x,y,z).$$

If $f_3 = f_4$, then $f_4 = \tfrac{1}{2}(F_3 - F_5)$ so that

$$F(x,y,z) = \tfrac{3}{4} F_5(x,y,z) + \tfrac{1}{4} F_3(x,y,z). \qquad (1)$$

This is the expression that is used to calculated the frequency of cloud cover in all three space dimensions, by analysing the three-dimensional fields of F_3 and F_5. In practice the approximations used to derive equation (1) are not very sensitve to the assumption of symmetry of the f_i distribution.

3. Available data and analysis

Data for a 20-year period of frequencies of ⅝ cover at 15 levels (above station) up to 5000 ft were used from 54 stations in the United Kingdom, and from 46 stations for ⅜ cover. (The highest ground in the United Kingdom is at 4406 ft.) These stations are shown in Fig. 1. All heights were converted to heights above mean sea level and from these data the fields of frequency were analysed objectively using orthogonal polynomials as base functions (Dixon *et al.* 1972); but to increase the accuracy of the representation in the vertical, the data were split into three overlapping sets covering the height ranges 0–800 ft, 500–2000 ft and 1200–5500 ft. Polynomials were evaluated to third order in all three dimensions, so that the analysed fields were represented by 20 coefficients.

From these analyses the frequencies of cloud cover of ⅜ or more and of ⅝ or more were calculated for a particular area of the United Kingdom, using the appropriate average height of ground. At heights falling in the overlap ranges (500–800 ft and 1200–2000 ft), a linear interpolation between the values for the two height ranges was used. Application of equation (1) then gives the estimate of cloud immersion frequency.

4. Results

Before looking at cloud immersion data, first look at maps of the frequency of cloud at or below specific heights. The frequency of cloud cover at or below a height of 500 ft is shown in Fig. 2. Everywhere over the United Kingdom frequencies are very low, nowhere exceeding 6% of the time. Highest frequencies are over the south-west of England and down the east coast, especially over East Anglia. Cloud at such a low height is usually stratus. Mansfield (1988), in an investigation of stratus distrubution over the United Kingdom, identified two summer regimes and one winter regime largely responsible for stratus. One of the summer regimes gives advection stratus/fog on south-western coasts and the other is associated with north-easterly flow and gives highest frequencies of stratus down the east coast, and especially over East Anglia. These regimes of advection

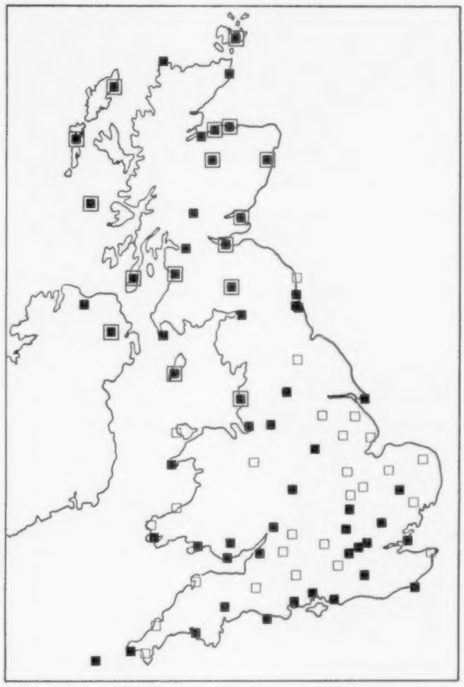

Figure 1. Stations included in the analysis. Solid squares indicate stations for which data were based on ⅝ cloud cover and open squares on ⅜ cover. (For 16 stations both were available.)

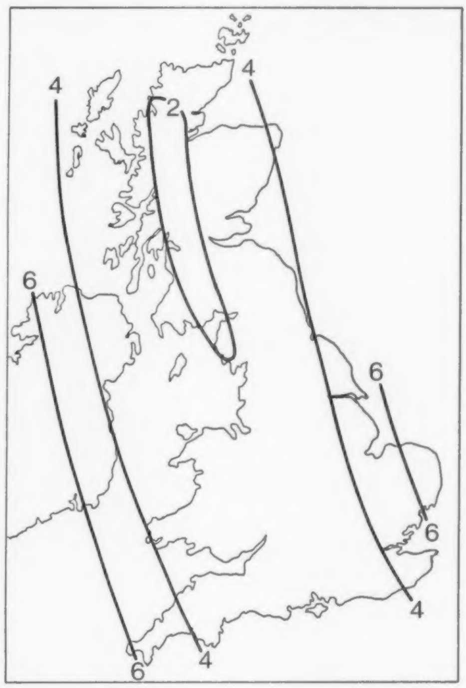

Figure 2. Frequency of cloud cover (%) at 500 ft above sea level.

stratus are the main reason for the form of the cloud frequencies at 500 ft shown in Fig. 2. The third, the winter regime, identified by Mansfield is associated with anticyclonic southerly flow and gives inland stratus due to local cooling.

The pattern of cloud frequency at or below 2000 ft (Fig. 3) shows lowest frequencies over north-east Scotland, with less than 15% frequency. This rather low frequency is probably due to the sheltering effect of the Scottish Highlands, causing a drying of the air in flow from western quadrants. Highest frequencies are in south-west England, East Anglia, and the Western Isles of Scotland, where frequencies reach 25%. Most of the cloud at or below 2000 ft is again likely to be stratiform, but some contribution from cumulus is probable, especially in coastal regions where humidities are higher and hence cloud base is lower.

The results of this analysis (obtainable on request from the author) may be used to derive cloud immersion frequencies on any spatial scale for which land height data are available; but, for illustration, average cloud immersion frequencies are given in Fig. 4 for 15 km squares over Northern Scotland. Highest immersion frequencies of 24% occur over the Cairngorm Mountains, where there are several peaks of over 4000 ft. The immersion frequency, given by the analysis, for the highest summit in the Cairngorms (Ben MacDhui, 4296 ft) is 42%.

Acknowledgements

The author is grateful to the Meteorological Office for the provision of the data, and to D.A. Mansfield for help and advice.

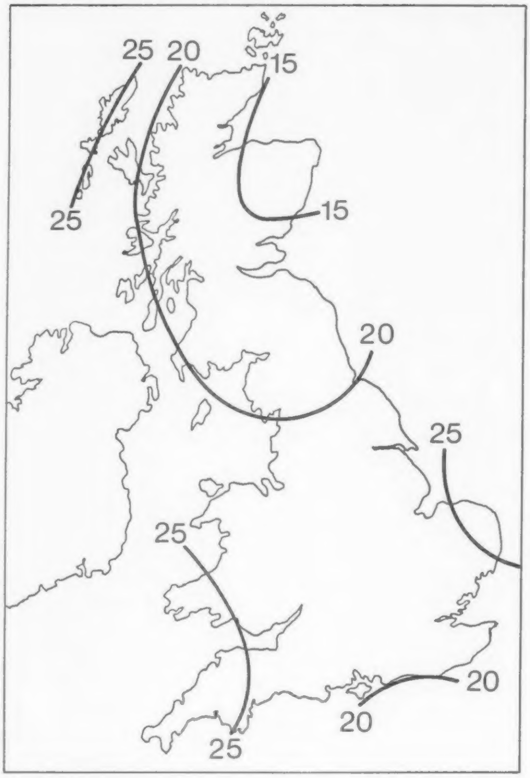

Figure 3. Frequency of cloud cover (%) at 2000 ft above sea level.

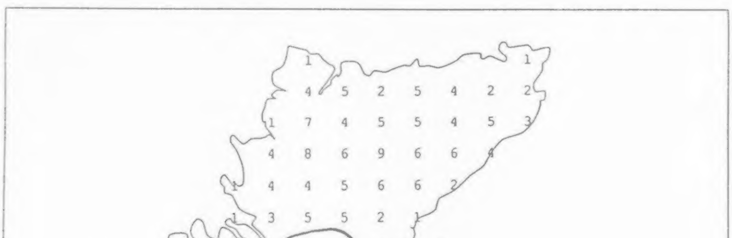

Figure 4. Cloud immersion frequencies (%) for Northern Scotland, averaged over 15 km squares. Contours of 10% and 20% are shown.

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Review

Prediction and regulation of air pollution, by M.E. Berlyand. 164 mm × 244 mm, pp. xiii+312, *illus*. Dordrecht, Boston, London, Kluwer Academic Publishers, 1991. Price Dfl.175.00, $108.00, £61.00. ISBN 0 7923 1000 4.

Question: 'Which is the oldest surviving area of research in the Meteorological Office (discounting the everlasting struggle to improve weather forecasting)?'

Answer: 'Surprisingly, it is the study of airborne pollution dispersion which started in the Office in about 1916 when poisonous gas was used as a weapon of war in the trenches.'

You might think we'd learnt a thing or two in those 75 years — and I think we have. On good days, one is tempted to think a very great deal has been learnt, not just in the Office but worldwide — just look at the fat books on the subject. Then comes the bad day! The telephone rings; a caller has a dispersion problem — it's a bit complex, with odd-shaped buildings and a steep valley next-door and downwash from the stack and .... A bit too difficult even for our latest up-market dispersion model with all the most recent science in it. Shattered you tell the caller the best thing he can do is to get it physically modelled in a wind-tunnel, theory cannot fully solve his problem, it can only guide him.

I think this anecdote reflects a tendency in the West to let theory and more practical procedures advance together as complementary partners. Overall, I believe this makes good sense and, aware of the uncertainties involved, we have been rather reticent to push the theory forward beyond what seems sensible in some difficult areas. On the other hand, scientists in Eastern Europe, and in Russia in particular, have apparently tended to develop theories and obtain complex solutions to problems that we have tended to model more tentatively or at best more empirically.

Professor Berlyand's book opens the window to what has been going on in the Soviet Union in the way of practical dispersion modelling. It reveals that many very important issues have been considered — many more than have been really worked on in the West. To give but one small example: the dispersion of gases emanating from a long slit running the length of the roof of an aluminium smelter. Often the approach has been theoretical, as implied earlier, but sometimes the suggested method has had to be empirical. In addition the book contains many of the advances made in the West; lots of references to western studies underline that.

It all makes fascinating reading — a new insight into a world of research all too little revealed in this depth before. Whilst I doubt it will revolutionize what is currently done in the West, I think it will make many of us think about our methods and thereby have a more subtle influence.

A little disappointingly there are many mis-spellings, particuarly of names, and other small but important typographical errors. Particularly disturbing is the occasional use of misleading terminology: to give one example, by 'light' pollutants the authors means 'passive' pollutants, not pollutants whose density is significantly less than that of air!

However these little irritations aside, this is a very important book with a rightful place on the shelf of any pollution meteorologist, and is otherwise very well produced and pleasing to use.

F.B. Smith

Fractals: endlessly repeated geometrical figures, by H. Lauwerier. 139 mm × 216 mm, pp. xiv+209, *illus*. London, Penguin Books, 1991. Price £9.90. ISBN 0 14 014411 0.

This book, an English translation of a work first published in the Netherlands in 1987, deals mainly with the basic mathematics of fractals rather than their applications or occurrence in nature. An appendix of computer programs illustrating the text enables readers with personal computers to generate fractals for themselves. The book is aimed at a wide audience and therefore assumes only a limited mathematical knowledge. Concepts such as number systems other than base ten, Cartesian co-ordinates, irrational numbers and infinite sets are explained in the early chapters. No familiarity with complex numbers is assumed or required but an appendix briefly indicates their use in simplifying some of the mathematics.

After a brief description of work on the length of the British coastline by L.F. Richardson (who is described as a 'somewhat eccentric English meteorologist'), the author describes various types of meandering curves. This is in line with his definition of a fractal as 'a geometrical figure in which an identical motif repeats itself on an ever diminishing scale', a definition which disguises the links between fractals and chaos. The well-known fractals of Sierpinski, Koch and Minkowski, all older than the term 'fractal' itself, are described as well as dragon curves (formed by repeated folding of a strip of paper), spirals, tree fractals and star fractals. Programs to draw all of these are included. A chapter for the mathematically minded reader describes methods for computing fractals of this type using similarity transformations. The backtracking method which is both fast and requires little storage is outlined and illustrated with programs.

It is not until half way through the book that the concept of chance makes its first appearance. This precipitates a succession of fascinating, and often deep, mathematical topics: Brownian motion, chaotic behaviour, Feigenbaum's number, attractors and Julia and Mandelbrot sets. Pure mathematicians will be disappointed to find only two of the book's eight chapters devoted to these subjects. A few illustrative programs are given but some of these topics stretch the present capacity of small computers. (A program to outline the Mandelbrot set is easily the longest running of all those listed.)

The book is well printed and contains a number of attractive illustrations of Julia fractals and detail of the Mandelbrot set as well as two spectacular fractal landscapes from Mandelbrot's book *The fractal geometry of nature*, all in colour but with little or no comment. A few typographical and other errors were detected including the incorrect description of the Mercator projection as 'the projection of a sphere from its centre onto a vertical cylinder surrounding it'. A short bibliography gives suggestions for more advanced reading.

The computer programs presented, written in BASIC for a PC with a high-resolution monochrome screen, form an essential feature of the book. They range from simple ones for drawing spirals to those capable of drawing various repeated-motif fractals at any specified level of detail. A few generate dust fractals illustrating chaotic behaviour. There is a certain fascination in watching a fractal design appearing on the screen like a time-lapse film of a fanatical portrait painter — readers familiar with basic will not be able to resist altering the data input to some programs to see what happens (some suggestions are given in a chapter entitled *Making your own fractals*), or modifying them to produce more detail. Most programs are less than 25 lines long and, although they contain few comments, all are referred to in the body of the text where further description can usually be found. (The graphics statements used are briefly described for users needing to convert to other programming languages.) Of course, accuracy is particularly important where computer programs are presented so it is satisfying to report that this reviewer has tried all of the 41 programs and found them to work as described.

The book cannot be described as a meteorological book — readers interested in the applications of fractals and chaos to clouds, turbulence and predictability will have to look elsewhere. But understanding of any new or unfamiliar scientific topic implies an initial familiarity with basic concepts. Within the limitations of its view of fractals as mathematical curiosities with aesthetic visual appeal rather than a subject related to modern mathematical techniques for describing the real world, this book succeeds in giving the reader a feel for fractals, not least through its computer programs. With these you will be able to demonstrate your skill in computer art to your friends. It certainly makes a refreshing change from holiday slides or home movies.

B.R. Barwell

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Natural weather wisdom, by Uncle Offa (Hanley Swan, Worcester, Images Design and Print Ltd, 1991. £9.50) contains many saws and sayings used by our forefathers as a guide to future weather. This, of course, entails observation of nature and types of weather on Saints' Days etc. ISBN 1 85421 146 3.

Fundamentals of weather and climate, by J.F.R. McIlveen (London, New York, Tokyo, Melbourne, Madra, Chapman and Hall, 1991. £19.95) is an expanded, new edition of *Basic meteorology: A physical outline*. It attempts to collocate the theory and actuality of atmospheric behaviour. ISBN 0 412 41160 1.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

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April 1992

Edited by R.M. Blackall
Editorial Board: R.J. Allam, R. Kershaw, W.H. Moores, P.R.S. Salter, J. Gloster

Vol. 121
No. 1437

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ISSN 0026–1149

ISBN 0-11-728982-5

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